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13. ABSTRACT *(Maximum 200 words)*
This project tested the original equation (OSE) in which sweating rate, msw (g * m^-2 * h^-1) = 27.9 * Ereq * Emax^-0.455, Shapiro et al. (EJAP 48: 83,1982). OSE predicts msw over wide heat stress conditions (HS), clothing systems including chemical protective (CPS), and metabolic activities. Ereq is required sweat loss calculated from heat balance and (Emax) is the maximum evaporative power of a thermal environment. OSE is suitable over a limited HS up to 2-h and work rates < 450W. Another objective was to develop a new algorithm or correct the OSE so that reliable fluid replacement guidelines can be constructed for work times > 2-h. USARIEM studies revealed that OSE in a Heat Stress Decision Aide (HSDA) over-predicts actual msw over wide HS, work rates, and times. Overpredictions in msw often lead to over-hydration problems. Data from 101 volunteers (80 men and 21 women) were analyzed including experiments at various activity levels over wide HS (Ta = 15°C - 46°C, Pw= 2 - 33 Torr and (V) = 0.4 - 2.5 m*s^-1) and various CPS with body armor. Studies included 4 separate chamber studies, 1 USARIEM field study & 1 study outside the U.S. Data were analyzed using fuzzy piecewise regression. OSE predicted high values (p< 0.003) compared to observed msw. We recommend HSDA incorporate the algorithm: msw = 147+ 1.527*(Ereq) - 0.87*(Emax), which accounts for effects of heavy work, CPS, body armor, 8h work, and is not gender specific. A correction to OSE is: msw = 147*exp (0.0012*OSE). These equations require testing over wider effective radiant loads in the field (Solar Load).

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Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRMC Regulation 70-25 on the use of volunteers in research.

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USARIEM TECHNICAL REPORT T07-##

CORRECTIONS TO THE SHAPIRO EQUATION USED TO PREDICT SWEATING AND WATER REQUIREMENTS

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BACKGROUND

A person's fluid balance and thermoregulatory equilibrium are essential for peak performance. Dehydration to levels exceeding 2% normal body mass and/or elevation of body temperature above 38.5°C are associated with reduced physiologic function and cognitive performance, and these impairments increase with increasing levels of body water loss, particularly in hot environments. Verification of valid and accurate fluid replacement algorithms for individuals (including, but not limited to firefighters, police personnel, athletes, and Warfighters) is a critical step in the development of "smart," personal guidelines and computer devices that can be implemented to optimize performance and prevent heat injuries. The Institute of Medicine (IOM 2005) has identified the "development of capabilities to predict hourly and daily water requirements based on metabolic rate, climatic conditions, and clothing" as a research priority.

Adequate hydration and core temperature equilibrium are essential for the prevention of heat-related illnesses and for sustaining peak physical and cognitive performance. Hydration is particularly important during training and field operations, especially under hot climatic conditions. Evaluation of the current operational water requirement guidelines using a systematic physiologic approach will enhance a better decision-making process regarding activity in hostile environment conditions faced by both military and civilian populations.

During regular military activity there are about 120 heat-stroke injuries each year, which are associated with a $10M/y cost (3,31); see also http://asma.army.mil). In the military population, dehydration is a co-morbidity factor in 20% or more reported heat casualties (3). Validations of fluid requirements and physiological strain assessment improve safety and performance, facilitate mission planning, optimize hydration and logistical efficiency, and help personnel overall in conduction operational missions. Furthermore, evaluation of the current guidelines, obtained from studies performed on a wider database, should address broader physiologic issues pertinent to both military and civilian operational needs where there is currently a gap in operational knowledge. In addition, this study effort should provide a better decision-making process regarding activity in hostile environment conditions, which eventually will help in decreasing the expenses associated with physical and heat stroke injuries. Algorithms that are easily migrated into current rational and empirical models addressing correct fluid requirements and physiological strain assessment can improve the safety and performance of Warfighters and optimize hydration and logistical efficiency.

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EXECUTIVE SUMMARY

The objective of this project was to cross validate the original equation, OSE, in which sweating rate ($g \bullet m^{-2} \bullet h^{-1}$) = $27.9 \bullet E_{req} \bullet (E_{max})^{-0.455}$, which was developed by Shapiro et al. (33) to predict rate of sweat loss over wide environmental conditions, clothing systems, and metabolic activities. E_{req} is required sweat loss calculated from heat balance, and E_{max} is the maximum evaporative power of a thermal environment. Within the limits of the data, the equation has been shown to be a valid estimator of sweating rate for a variety of heat stress exposures up to 2 h and work rates limited to less than 450 W. The second objective was to develop a new prediction algorithm or correct the previous one so that reliable fluid replacement guidelines using such equations can be constructed in the future for more extended work times greater than just 2 h, the exposure time present in the original study database. The need to develop a new prediction equation stems from results of recent studies at USARIEM that revealed that the original equation embedded in a Heat Strain Decision Aide (HSDA) computer model over predicts actual sweating responses over wide environmental extremes, work rates, and work periods. Overpredictions of sweating rate (and the required fluid intake to fully replace the expected sweat loss during extremes of heat loss) can lead to over-hydration problems. A USARIEM database was secured consisting of 101 volunteer subjects (80 men and 21 women) who completed experiments at various activity levels over wide environmental ambient conditions. T_a ranged from 15°C to 46°C, ambient water vapor pressures varied from P_w= 2 to 33 Torr, and air movements (V) were from 0.4 to 2.5 $m \bullet s^{-1}$. Subjects wore various military clothing systems including chemical protective clothing and body armor. Raw data were obtained from 4 separate chamber studies and 1 field study conducted at USARIEM, and 1 laboratory study conducted by the Defence R&D Canada (DRDC), Toronto. Each element of the comprehensive heat balance equation was analyzed. Data were analyzed using fuzzy piecewise linear and nonlinear regression analyses to establish appropriate change points in sweat loss per time points. It was established that the original Shapiro algorithm tested in this study (101 subjects, longer work durations from 4-8 h, and a variety of clothing systems) predicts markedly high values in sweating rates. The most important finding of the current study and recommendation is to substitute or modify the current HSDA program with a corrected algorithm: sweat loss ($g \bullet m^{-2} \bullet h^{-1}$) = $147+1.527 \bullet (E_{req}) - 0.87 \bullet (E_{max})$. This equation takes into account effects of heavy work and clothing factors, body armor, longer exposure times (8 h), and is not gender specific. Alternatively, a correction to the original equation can be used as a simple replacement: sweat loss = 147•exp (0.0012•OSE). These equations require testing over wider effective radiant loads in the field (effect of Solar Load) using a larger database.

INTRODUCTION

Maintaining heat balance by regulating core temperature within tolerable limits by having proper hydration levels over complex thermal environments is essential for peak human performance. Dehydration levels exceeding 2% of normal body mass coupled by elevations in core temperature above 38˚C are associated with reduced physical and cognitive performance (6,7,16,30,31,34), particularly in hot environments. Likewise, core temperatures below 36˚C can also lead to hypothermia and cold injury.

The U.S. military currently uses two prediction models, based on two different concepts, to predict sweating rates and core temperatures of Soldiers during operational stress. The U.S. Army Research Institute of Environmental Medicine (USARIEM) Heat Strain Model (HSDA) is an empirical model that includes equations to predict sweating rate, work/rest cycles, and maximal working times during different levels of metabolic rate and exercise intensity (13,15,27). These algorithms have been used to prepare military guidance regulations for water needs and work/rest cycles during training and deployment (e.g., FM 10-52; FM 21-10; TBMED-507). Recently, these algorithms were embedded in a digital mini heat strain monitor (HSM), which is a rugged, pocket-sized, advisory heat strain device that also outputs integrated WBGT and, therefore, may be applied in the field or for various training maneuvers. Predictive equations for implementing work/rest disciplines with various clothing systems, environments, or workload sequences in the model are based on a series of functions that cascade into final output values of work/rest cycles, water requirements, and maximum endurance times for a given environmental activity and clothing system scenario.

The second thermoregulatory-cardiovascular model, called SCENARIO (11,18), is a rational Soldier-physiologic model designed to simulate the time course of heat strain observed during military, industrial, and athletic settings. In this model, the human body is modeled as a single cylinder containing six compartments: [1] a central core representing the heart, lungs, and splanchnic regions, [2] a muscle layer, [3] a subcutaneous fat layer, [4] a vascular skin layer, [5] a superficial vascular skin layer, and [6] a central blood compartment. Rates of metabolic heat production in the core, fat, and vascular skin compartments are assumed to be fixed percentages of total resting metabolism. Heat production of the muscle layer is variable, depending on total energy expenditure and external work performed. It is assumed that the blood and skin compartments produce an insignificant amount of heat. The SCENARIO model (11) can be easily migrated into a robust military operational computer simulation software product for use in planning and mission evaluation of Soldier's individual variability.

In 1972, Givoni and Goldman (15) developed an empirical approach to predict core temperature response. They inferred that for any given combination of metabolic rate, environment, and clothing, a theoretically determined equilibrium maximal point of core and skin temperatures would be generated, and unified equations could be constructed to predict that set limit. A series of predictive equations were developed and were proved useful in describing human heat exchange while subjects wore a variety of clothing systems that matched with core temperature pattern response during rest, work, and recovery in the heat.

The predictive equations for implementing work/rest cycles with various clothing systems, climates, or workload sequences in the original Givoni-Goldman model were based on a series of theoretical regression equations that simulated the thermoregulatory function (27). The main equation in the model was one that established the difference in core temperature expected at theoretical equilibrium for a given environment, work rate, and clothing system. The core temperature at every minute was dependent on the initial core temperature, the equilibrium core temperature, and the time in the period from the end of a proceeding delay time during work or rest. A significant number of training guidelines for work/rest cycles in the U.S. Army, the Israeli Defense Forces, the Technical Cooperation Program (TTCP) countries, and many other military training guidelines were based on these modified equations (13).

Crucial to the above model's operational application, and embedded in its model computer code, is the Shapiro sweating rate algorithm currently used in the HSDA, a modern sequel of the original Givoni-Goldman model. The latter model was developed from limited laboratory experiments on men only for energy expenditures ranging from approximately 75 W (rest) up to 475 W (moderate intensity work for a dismounted Soldier) over a range of environmental conditions (20°-54°C and 10%-94% relative humidity [RH]) while wearing shorts and T-shirt, outdated military fatigues, and CB garments. It is also only applicable to predict sweating responses for men (33). The derived equation is shown below:

$$\text{Sweating rate } (g \bullet m^{-2} \bullet h^{-1}) = 27.9 \bullet E_{req} \bullet (E_{max})^{-0.455} \qquad \text{(Eq. 1)}$$

where E_{req} is the evaporation required to maintain heat balance at any given core temperature and E_{max} is the maximal evaporative capacity of the environment. This equation has been used to predict water requirements, assuming the fluid intake (L/h) replaces the expected water lost by sweating in a fully heat-acclimated person (sweating rate x body surface area (BSA) x 10^{-2}, L/h).

A caveat to the use of model analyses that overpredict sweat losses is that excessive and persistent overdrinking can lead to a relatively rare but potentially lethal condition known as symptomatic hyponatremia or water intoxication (6,10,23,26). Current guidelines found in various military operational manuals have been shown to overpredict requirements. Use of inaccurate sweat loss predictions can lead to incorrect hydration needs (forced or permissible) during extreme heat and exercise challenges (4,22,23). An outbreak of exercise-induced hyponatremia cases in the U.S. military (10) led to a revision of the recommended hourly fluid consumption guidelines during work in hot weather (22).

While the array of exercise and environmental conditions would appear to have covered adequately a broad range of climatic conditions using the 2-h Shapiro equation to predict water requirements, only resting exposures were included at air temperatures below 35°C. Additionally, the clothing evaluations were done using static manikin (still air) evaluations and do not cover modern clothing materials now being tested (employing dynamic manikins) and used by military developers for the modern Warfighter. Because accurate prediction of water requirements is essential for more than just mission requirements in hot climates, it is imperative that physiologic algorithms be accurately validated to predict sweating rates over wider environments, including both temperate and cool climatic zones over which Warfighters conduct operations.

The purposes of this study were the following: [1] to assess the accuracy of the original Shapiro sweat loss prediction equation (established solely using a 2-h time frame) using a wider database that includes extended time periods during prolonged exercise (8 h), heavy work rates, and contemporary clothing systems including body armor; [2] to seek to develop new algorithms that can predict sweating requirements that are more accurate over extended periods, and [3] to provide, if possible, a correction to the original Shapiro equation (OSE) that is applicable and easily migrated into the current HSDA for use during more extended periods of exercise in cool and warm environments. The hypotheses, based on current research and literature results (4,22,23), were that OSE overestimates sweating rates over extended periods of exercise and, therefore, leads to excessive estimates of water requirements for particular operational needs. A new algorithm based on a more extensive database than the original would allow a more finite estimation of water requirements over wider environments and exercise intensities. Additionally, a correction to the old equation should allow a reasonable prediction of the water requirements without scrapping a 25-year history of operational doctrine related to water requirements, and should prevent unnecessary water loading. Such an improved algorithm would be a useful feature for implementation in present HSDA water requirement predictions decisive in future military and civilian operational applications.

METHODS

DATA ANALYSIS

The database consisted of 101 volunteer subjects (80 men and 21 women) who completed experiments at various activity levels over wide environmental ambient conditions. T_a ranged from 15°C to 46°C, ambient water vapor pressures varied from P_w= 2 to 33 Torr, and air movements (V) were from 0.4 to 2.5 m•s^{-1}. Subjects wore various military clothing systems. Each protocol was approved by the appropriate institutional review boards, and all volunteers were informed both verbally and in writing of the objectives and procedures of the respective study. No identifications of a given volunteer's personal records were present in the current spreadsheet database.

Raw data were obtained from 4 separate chamber studies and 1 Field study conducted at USARIEM, and 1 laboratory study conducted by the Defence R&D Canada (DRDC), Toronto (13). These studies are described in the following sections:

(a) USARIEM protocol H98-04 (Montain, PI). Data were examined from 19 previously heat acclimatized Soldiers (13 men and 6 women) who completed all experiments dressed in hot weather Battle Dress Uniforms (BDUs, clo value 1.08; im/clo= 0.49). Extensive study details can be found in Montain, et al.(22). In brief, individuals completed 12 randomize exercise-heat stress trials in which they walked at 3 exercise intensities either at 250, 425 and 600 W in three humid environments (Ta=28°C/Pw=21.3 Torr; Ta=32°C/Pw=26.8 Torr and Ta=36°C/Pw=33.4 Torr). In other studies they walked at 425 W in three dry environments (Ta=36°C/Pw=11 Torr; Ta=41°C/Pw= 14.6 Torr; and Ta=46°C/Pw=19 Torr). Dry heat stress trials were completed following a humid test condition. Appropriate work/rest cycles for each exercise task were initially determined using the HSDA (27) over a 2-h total exposure. Rectal temperatures, heart rate, and oxygen uptake from indirect calorimetry (2-min Douglas bag collection) were measured. Missing mean skin temperature (T_{sk}) data, required to calculate pertinent heat balance equation parameters, was estimated using Saltin's (28) equation: T_{sk}=0.215•Ta+26.6 (±0.5 SEE). Whole body sweating rates were calculated from changes in pre- and post-exercise body weights after correction for clothing weights, water intake, urine production, and estimates of metabolic water loss (m_{res}) and respiratory heat loss (E_{res}) (see Appendices A & B).

(b) USARIEM protocol H03-14 (Montain, PI). Details can be found in Cheuvront et al. (4). Thirty-nine healthy individuals participated in this study. The clothing ensemble was the U.S. Army woodland BDU with field cap, sleeves down (clo=1.08, i_m/clo=0.49 at wind speed 1 m/s), and athletic shoes. Test sessions lasted either 2- or 8-h. Twenty-one volunteers (16 men and 5 women) participated in the 2-h experiments, and physical characteristics for this group are shown in Table 1. Eighteen different volunteers (17 men and 1 woman) completed the 8-h experiments, and their characteristics are shown in Table 2. Tables 1 and 2 also describe the 7 different levels of environmental stress, work: rest cycles, VO_2 at each work intensity, and sweat loss observed. In the 2-h study trials, volunteers were not heat acclimated, while in 8-h experiments, volunteers were previously heat acclimated.

Table 1. Key descriptive and physiological data for 2-h experiments in Protocol H03-14 used in developing the present algorithm.									
Trial	T_a (^oC)	Pw (Torr)	Work:Rest Cycles #(min)	N Males Females	BSA (m^2)	Body Weight (kg)	T_{sk} (°C)	VO_2 (L/min)	SR (L/h)
A1	15	6.4	2x (50:10)	**12M**	**1.94±0.15**	**77.6±8.8**	**29.3 ± 1.0**	**0.94 ± 0.14**	**0.135 ± 0.079**
				4F	**1.70±0.03**	**64.3±4.2**	**28.2±0.82**	**0.79±0.17**	**0.188±0.086**
A	15	6.4	2x (50:10)	**13M**	**1.96±0.14**	**79.7±9.3**	**28.7 ± 0.8**	**1.49 ± 0.17**	**0.305 ±0 .136**
				2F	**1.68**	**60.4**	**28.7**	**1.3**	**0.319**
B	15	6.4	2x (50:10)	**13M**	**1.96±0.14**	**79.7±9.3**	**29.1±1.0**	**1.99±0.21**	**0.472±0.170**
				2F	**1.68**	**6.4**	**27.5**	**1.57**	**0.424**
C	20	8.8	2x (50:10)	**14M**	**1.96±0.14**	**80.7**	**31.1 ± 0.8**	**178 ± 15**	**0.220 ± .089**
				1F	**1.63**	**56.9**	**31.34**	**0.81**	**0.165**
D	20	8.8	2x (50:10)	**15M**	**1.98±0.13**	**80.9±8.9**	**30.2±1.08**	**1.45±0.19**	**0.410±0.177**
				4F	**1.67±0.04**	**62.6±5.7**	**30.4±0.47**	**1.14±0.13**	**0.346±0.084**
E	20	8.8	2x (50:10)	**15M**	**1.97±0.14**	**80.5±9.4**	**30.3±1.15**	**2.03±0.26**	**0.625±0.199**
				2F	**1.69**	**63.5**	**29.6**	**1.49**	**.498**
F	25	11.9	2x (50:10)	**11M**	**1.96±0.11**	**80.2±8.9**	**31.8±0.55**	**1.03±0.16**	**0.321±0.102**
				2F	**1.68**	**60.35**	**31.1**	**0.84**	**0.421**
G	25	11.9	2x (50:10)	**9M**	**1.95±.12**	**80.0±9.5**	**31.5±0.92**	**1.47±0.20**	**0.479±0.171**
				1F	**1.73**	**63.8**	**30.9**	**1.26**	**0.515**
H	25	11.9	2x (50:10)	**10M**	**1.95±0.11**	**80.5±8.9**	**32.1±0.62**	**1.99±0.27**	**0.755±0.237**
				1F	**1.63**	**56.9**	**31.6**	**1.54**	**0.558**
I	30	15.9	2x (50:10)	**10M**	**1.95±0.11**	**80.5±8.9**	**33.5±0.75**	**1.98±0.26**	**0.935±0.317**
				1F	**1.63**	**56.9**	**33.1**	**1.45**	**0.702**

Legend: n (number of subjects and gender completing experiment), T_a (air temperature), Pw (ambient water vapor pressure), T_{sk} (mean skin temperature), SR (observed sweating rate). All data are means ± SD except when n <3. Wind speed for all experiments was 1 m/s.

Table 2. Key descriptive and physiological data for 8-h experiments in Protocol H03-14 used in developing the present algorithm.									
Trial	T_a (^oC)	Pw (Torr)	Work:Rest Cycles #(min)	N Males Females	BSA (m^2)	Body Weight (kg)	T_{sk} (°C)	VO_2 (L/min)	SR (L/h)
J	40	22.1	6x (60:20)	**12M**	**2.03±0.14**	**84.7±12.4**	**35.9 ± 0.61**	**1.11 ± 0.21**	**0.667 ± 0.114**
				1F	**1.63**	**55.3**	**36.2**	**0.775**	**0.404**
K	35	12.7	6x (60:10)	**15M**	**1.97±0.12**	**80.2±9.8**	**34.4 ± 0.5**	**1.39 ± 0.21**	**0.569 ±0 .062**
				1F	**1.62**	**54.8**	**34.12**	**0.92**	**0.405**
L	35	12.7	6x (60:10)	**15M**	**1.99±0.15**	**81.7±12.9**	**33.9±0.5**	**1.05±0.15**	**0.452±0.058**
M	27	10.7	6x (60:10)	**14M**	**1.98±0.15**	**81.7±12.9**	**32.3 ± 0.6**	**1.44 ± 0.23**	**0.406 ± 0.096**
				1F	**1.63**	**55.7**	**31.83**	**0.96**	**0.263**
N	27	10.7	6x (60:10)	**12M**	**1.98±0.16**	**81.1±13.9**	**32.7±0.64**	**1.05±0.14**	**0.269±0.05**
				1F	**1.63**	**55.6**	**33.0**	**0.770**	**0.153**
O	20	8.8	6x (60:10)	**12M**	**1.97±0.16**	**80.9±14**	**30.6±1.15**	**1.39±0.22**	**0.229±0.087**
				1F	**1.63**	**55.1**	**30.3**	**0.847**	**0.162**

Legend: n (number of subjects and gender completing experiment), T_a (air temperature), Pw (ambient water vapor pressure), T_{sk} (mean skin temperature), SR (observed sweating rate). All data are means ± SD except when n <3. All subjects previously heat acclimated. Wind speed for all experiments was 1 m/s.

(c) USARIEM protocol H05-12 (Cheuvront, PI). Details can be found in Cheuvront (5). Thirteen men completed 3 experimental trials in a hot, dry environment (Ta= 35ºC, Pw=12.7 Torr, 1m/s wind speed). The U.S. Army BDU was worn in all 3 trials, either alone (trial BDU), combined with Interceptor Body Armor (trial IBA), or combined with Interceptor Body Armor and spacer vest (trial SP). Four hours of intermittent treadmill walking was performed (50 min walking: 10 min rest intervals). In the BDU trial, walking speed was 1.56 m/s with a grade of 3%. In the IBA and SP trials, the grade was reduced to 2% to compensate for the added armor weight, which allowed examination of the clothing contributions to heat strain independent of added load carriage.

(d) H06-14 (Cadarette, PI). One female and five male volunteers did continuous exercise (treadmill speed at 80.2 m/min;Vo2 ranges 0.86 to 1.24 L/min) for 2 h while dressed in BDU + IBA, as in (c) (IBA: clo = 1.35, i_m/clo = 0.27 at wind speed 1 m/s). Environmental conditions were Ta=30°/Pw=16 Torr; Ta=35°C/Pw=32 Torr; and Ta=40°C/ Pw=11 Torr. All procedures were as outlined in (c) above.

Clothing

All clothing characteristics (insulation, clo; vapor resistance, i_m/clo) were measured on a sweating thermal manikin for each clothing configuration tested (BDU, IBA, SP). In the BDU trial, the BDU was worn with field cap, sleeves down, and athletic shoes, rather than field boots, to reduce blister formation (BDU: clo = 1.12, i_m/clo = 0.44 at wind speed of 1 m/s). In the IBA trial, subjects also wore the Interceptor Body Armor vest to include front and rear ballistic protective inserts (throat and groin protection excluded). The outer vest is made of a fine Kevlar weave, and the protective plates of boron carbide ceramic with spectra shield backing. The total weight of the vest as used was 7.5 kg, and it covered ~25% of the total BSA (IBA: clo = 1.35, i_m/clo = 0.27 at wind speed 1 m/sec). In the SP trial, subjects also wore a 1-cm thick vest of proprietary knit fabric in between the Interceptor Body Armor and uniform. The spacer vest is designed to produce an air channel that can theoretically increase the potential for ventilation and evaporative cooling of the torso (SP: clo = 1.28, i_m/clo = 0.32 at wind speed 1 m/sec). The weight of the spacer vest was nominal (0.2 kg).

Procedures

At the start and conclusion of each trial, nude body mass was measured on an electronic precision balance scale (Toledo 1D1, Worthington, OH; accuracy ± 20g). To minimize differences in hydration state between trials, 250 ml water was given 1 h before starting exercise. Body mass measurements that fluctuated by less than 1% of the 10-day mean were considered normal. A similar hydration state from trial to trial was assumed. Additional fluid was given on the morning of a test only if body mass deviated downward by more than 1% of the 10-day mean (5).

Heart rate (HR) (Polar a_3, Polar Electro, Inc., Woodbury, NY) and core (intestinal) body temperature (T_c) (Jonah™ core body temperature capsule, Mini Mitter Company, Inc, Bend, OR) were measured continuously and recorded at 10-min intervals.

Independent Cross Validation Data Sets:

Ft. Bliss Field Study. A separate archival raw data set was obtained from a previous field study conducted at Ft. Bliss, TX, by USARIEM and used to test the algorithms. Details can by found in Santee et al. (29). In brief, 8 males (average body mass=80.5±15.2 kg SD; BSA = 1.97±0.18 m2 SD) walked at a pace of 2 mph for 12 miles (24 min continuous exercise with a 6-min break) on a calibrated track for 6 h. Subjects carried a 22-kg pack, and average heat production was maintained at 194.5±20.4 W•m^{-2}. Clothing systems were MOPP 0 (BDU: clo= 1.34/ im/clo=0.31 at 1m/s), MOPP 1 (clo=1.97/ im/clo=0.17 at 1 m/s), and MOPP 4 (clo = 2.44/ im/clo=0.12). Volunteers did night and day walks in the various clothing configurations. Core temperature was measured with a thermistor inserted 10 cm into the rectum, and 3-site skin temperatures were measured with heat flow discs; all data were collected using a Grant squirrel temperature recording device. Daytime ambient conditions were T_a=23°C/ Pw=1.6 Torr, with a mixed solar load estimated by the Effective Radiant Field at 500W•m^{-2}, resulting in an operative temperature (T_o) = 49.5°C (9).

DRDC, Toronto Data Set. Raw data sets from a completed laboratory study, as part of a report to The Technical Cooperation Program (TTCP) (13), were used to test the various prediction equations. Data from 13 males and 9 females (follicular phases of their menstrual cycle) were used to compare the various equations. Physical characteristics (±SD) were males, body mass, 82.7±12.5 kg; BSA, 2.01±0.16; females, body mass, 60.4±8.9; BSA,1.66±0.15. The ambient conditions were Ta = 40°C/ P_w= 11 Torr at V=0.4m•s^{-1}. Subjects exercised for 2 h (4 work:rest cycles of 15:15 min) or before their rectal temperature reached a peak value of 39.5°C, or heart rate became elevated no higher than 180 beats•min^{-1} for 3 min. Average M (±SD) of the male groups was 203.4± 24.1 W•m^{-2} and for the female group, average M was 187.5±17.4 W•m^{-2}. Rectal temperature was measured from a thermistor inserted 15 cm beyond the anal sphincter and mean skin temperature from a 12 point area weighted average recorded on strategic skin area sites. Subjects were dressed in Canada NBC clothing system previously evaluated by USARIEM manikin procedures and found to have a clo value of 1.88/ im/clo= 0.18 at V=1m•s^{-1} (14).

HEAT TRANSFER ANALYSIS PROCEDURES

Each element of the comprehensive heat balance equation (Appendices A & B) was determined from the raw data and concatenated to link together in a unified spreadsheet (Microsoft Excel®) for later model algorithm analysis using various statistical modules (STATISTICA®, Version 7, Tulsa, OK) and nascent proprietary mathematical code.

STATISTICAL PROCEDURES

Quasi-Newton Method

All concatenated data were analyzed using fuzzy piecewise linear and nonlinear regression analyses (35,36) to establish appropriate change points in sweat loss per time points in the data set, coded by trial, sex, and individual subject number, and derive intercepts for independent parameters derived from the heat balance equation (E_{req}, E_{max}) for the data set. A Quasi-Newton method was employed to derive regression parameters. In this method, the slope of a function at a particular point is first computed as the first-order derivative of the function (at that point). The "slope of the slope" becomes the second-order derivative, which reveals how fast the slope is changing at the respective point, and in which direction. The quasi-Newton method will, at each step, evaluate the function at different points in order to estimate the first-order derivatives and second-order derivatives. The analysis technique then uses this information to follow a path towards the minimum of the loss function (35). The fuzzy piecewise is more robust than conventional methods and not sensitive to outliers or irregular data, as was found in the present data set (see Figures 1 and 1A). The technique, as constructed for this study, is also suitable for long-term time series predictions of specific variables (35). Comparison of the original Shapiro equation predicting sweat loss and water requirements was initially done against observed data to obtain residual analyses to ascertain how much the Shapiro equation deviated from the observed data. Next, the new fuzzy piecewise equation (35) was compared against the original Shapiro equation and the observed raw data secured for each separate trial. Corrections to the original Shapiro equation were derived by independent piecewise regression analyses incorporating an iterative approach to obtain the most optimum equation (exponential, log fit, etc.) and test the significance of the derived regression coefficients (Wald statistic) that fit the database. The conditions were that the new equation prediction of sweat loss did not deviate from the observed data or the independently determined fuzzy piecewise equation by more than ±0.28 L/h (roughly ±150 $g \cdot m^{-2} \cdot h^{-1}$).

Data are expressed as means ±SD or ±SE, or as means ±95% confidence interval (CI). The differences in observed sweat loss, heat production, and the output from the various prediction equations were analyzed by a Factorial ANOVA design to include main-effects and interactions for categorical predictors (gender, all Trials). Both univariate (using a given single continuous dependent variable) and multivariate (multiple continuous dependent variables) designs were analyzed. If a significant F value was found for a given dependent variable, the Bonferroni adjustment procedure was used as a post hoc approach to locate critical differences at $P<0.01$ and considered statistically significant; correlations with a probability value greater than .01 (including those with p-values between .01 and .05) were considered non-significant.

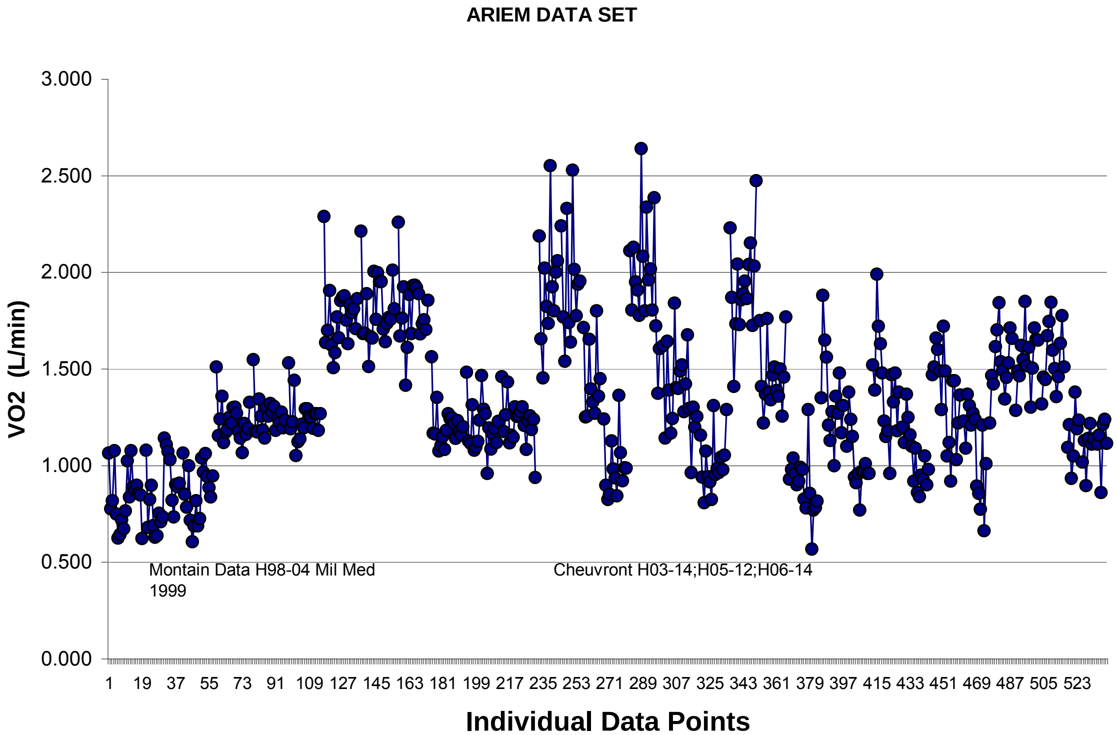
Finally, an independent cross validation analysis of the fuzzy piecewise equation was executed against two independent archival data sets: a field study in which a group of men walked in various levels of MOPP clothing (0, I, and IV) (29) and using data in a lab study conducted at DRDC, Toronto (13) previously discussed in the Methods section.

RESULTS

Figure 1A shows the VO_2 obtained from each of the subjects during the various trials. Along with the other individuals' parameters (T_{sk}, clo, im/clo) and environmental parameters, heat production from the raw VO_2 was determined by the comprehensive heat balance to obtain Ereq (Appendices A and B).

Figure 1B shows observed sweating rates for each trial in the data set depending on exercise intensity, ambient condition, and clothing system worn. The observed sweating rates were compared with the original Shapiro equation (Eq. 1) to determine residuals.

Figure 1A. Oxygen uptake (VO_2) from the data set.



The E_{req} and the E_{max} obtained by solution of the heat balance equation for each individual and specific environmental parameter were used to derive a new equation using fuzzy piecewise regression, as described in the Methods section.

Table 3 shows the calculated mean heat production (M, $W \bullet m^{-2}$) and observed sweat loss (OSL, $g \bullet m^{-2} \bullet h^{-1}$) ±SE for each trial (Methods) separated by gender for the USARIEM data set. Following ANOVA tests, which might reveal whether there was any significant effect of gender, a Bonferroni post hoc (20) analysis was done on the data set. There was significant difference in OSL only between men and women within the moderate intensity exercise trials of Protocol H98-04, combining all dry and wet environments.

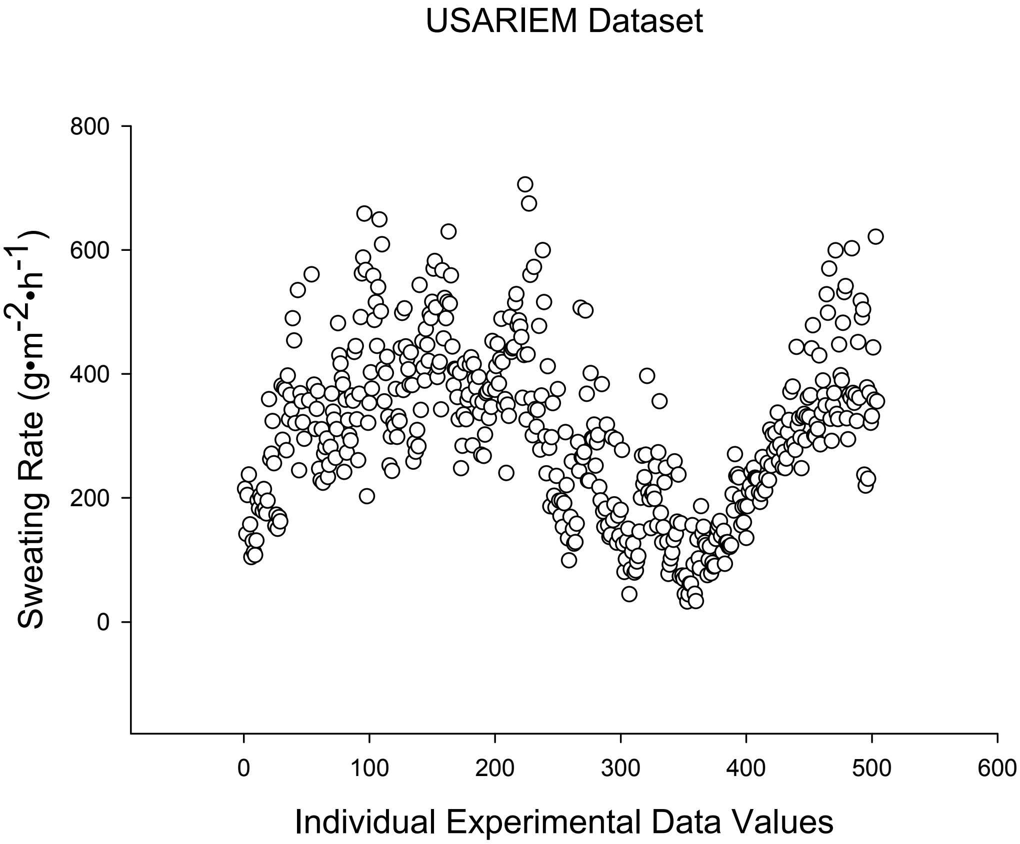
Table 3. Heat production (M, $W \cdot m^{-2}$) and observed sweat loss (OSL,$g \cdot m^{-2} \cdot h^{-1}$). Values are least squares means between males (M) and females (F) for combined data.

Cell	**Trial**	**Sex**	**M**	**M (±SE)**	**OSL**	**OSL (±SE)**	**N**
1	H98-04-L	M	163.04	8.87	295.21	18.35	32
2	H98-04-L	F	148.60	12.18	208.31	25.17	17
3	H98-04-M	M	224.00	5.84	407.13	12.06**	74
4	H98-04-M	F	252.24	8.37	332.59	17.29**	36
5	H98-04-H	M	329.18	8.25	443.96	17.06	37
6	H98-04-H	F	357.61	11.83	356.88	24.46	18
7	H03-14-B	M	252.42	3.53	224.72	7.30	202
8	H03-14-B	F	231.82	10.04	210.19	20.75	25
9	H05-12-B	M	284.66	13.92	353.21	28.78	13
10[a]	H05-12-B	F	NA	NA	NA	NA	
11	H05-12-I	M	287.79	13.92	407.64	28.78	13
12[a]	H05-12-I	F					
13	H05-12-S	M	289.52	13.92	420.47	28.78	13
14[a]	H05-12-S	F					
15	H06-14-I	M	213.07	12.96	362.12	26.79	15
16	H06-14-I	F	193.80	28.98	483.49	59.91	3

** $P \leq 0.01$, Bonferroni post-hoc test within trial cells; all others NS. SE= standard error; N= number of values within each group. [a]Not estimable due to lack of or small sample size.

Figure 1B shows the observed sweating rates during all experiments that were used to compare against the original Shapiro equation and analyzed to develop a new prediction algorithm.

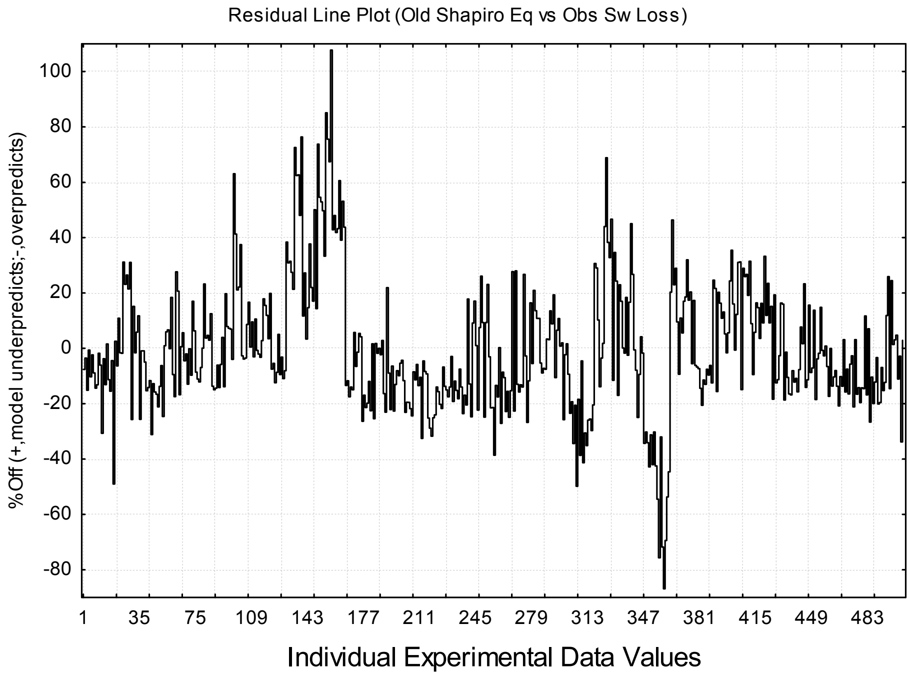
Figure 1B. Sweating rate from all experiments and individuals.



Noticeable are the extensive high points and depressions reflecting the variable sweating outputs of the individuals during the mixed work intensities and environmental conditions.

Figure 2 shows the results of the residual analysis comparing the output from the original Shapiro equation against the observed sweating shown in Figure 1A.

Figure 2. Residual line plot using output from the original Shapiro equation vs. observed data for sweat loss ($g \cdot m^{-2} \cdot h^{-1}$).



It is clear from Figure 2's plot of the residual values (comparison of a given observed sweat loss value minus the predicted value for each data point) that the original Shapiro equation overpredicted sweat loss by as much as 100% from the various trials, especially during heavy work intensities (H98-04), and under-predicted by some 80% during cooler trials (T_a=15°C). However, there is a range in the data in which the model predicts within ±20% of observed data particularly during easy work activities and mild heat stress conditions.

The data set was next examined to develop optimum regression parameters that would satisfy all experimental trials sufficiently (within an SEE of ±0.28 L/min [~±150 $g \cdot m^{-2} \cdot h^{-1}$] and coefficient of determination, R≥0.8). Since the data were collected at different times and contained disparate conditions (environmental stress, gender, acclimation states, work intensities from heavy to easy and various clothing systems), a non-linear fuzzy piecewise regression employing a Quasi-Newton solution (see Methods) gave the best resolution (35,36).

The reduced fuzzy piecewise regression algorithm (fPW) developed for the combined data set from a solution of E_{req} and E_{max} is:

$$\text{Sweating rate } (g \bullet m^{-2} \bullet h^{-1}) = 147 + 1.527 \bullet E_{req} - 0.87 \bullet E_{max} \qquad \text{(Eq. 2)}$$

resulting in an R = 0.89, which explained 78.94% of the variance in the disparate data set. For this analysis, E_{req} and E_{max} were determined from the individual heat balance equation and transformed by division of $W \bullet m^{-2}/(0.68\ W \bullet h^{-1} \bullet g^{-1})$.

Since it was determined that the output from the original Shapiro equation (OSE, Eq. 1) would probably not unify the data set and predict adequately (Figure 2), a similar iterative approach used to obtain Eq. 2 was run to correct the OSE using individual analysis of E_{req} and E_{max} in the data set. An exponential correction to Eq. 1 was successfully obtained after attempting various statistical algorithm solutions. This solution produced the following correction equation to predict sweating rates:

$$\text{Correction to sweating rate } (g \bullet m^{-2} \bullet h^{-1}) = 147 \bullet \exp^{[0.0012 \bullet OSE]} \qquad \text{(Eq. 3)}$$

where OSE in Eq. 3 is the uncorrected output from the original Shapiro equation (33):

$$\Delta\ m_{sw} = 27.9 \bullet E_{req} \bullet E_{max}^{-0.455} \qquad \text{(Eq. 1)}$$

Figure 3 shows a comparison of the OSE, the exponential correction to OSE, and the observed sweating rates from the present data set plotted against output values calculated with the new piecewise regression sweat prediction equation. The solid lines indicate negative (decreasing) exponential smoothing curves secured by a polynomial regression algorithm. In the latter regression, the weights that determine the influence of individual data points of the sweat loss on consecutive segments of a curve are calculated using a negative exponential function. Using this function, unnoticeable patterns of data response can be revealed. For instance, the OSE response curve is unremarkable within the range of 20-300 $g \bullet m^{-2} \bullet h^{-1}$ and is probably the optimum range that this equation should be applied; however, it begins to deviate from the corrected OSE prediction equation and the observed sweat loss data curves at about 320 $g \bullet m^{-2} \bullet h^{-1}$. There is a noticeable "break" in the OSE curve occurring around 500 $g \bullet m^{-2} \bullet h^{-1}$, which continues to a high ceiling point that is almost double the value denoted by the piecewise regression prediction output. Both the exponential correction to OSE output and the observed data match the piecewise regression output precisely up to a value of 500 $g \bullet m^{-2} \bullet h^{-1}$. Past this point, the exponential correction to the OSE equation begins to deviate upwards while the observed data curve exhibits a downward trend. The latter phenomenon may be perhaps owing to low sweating responses during low work intensity and/or cool environmental trial runs (T_a=15°C). Linear regression analyses (shown in the box insert to Figure 3) estimated by plotting the outputs of the 3 dependent variables (OSE, corrected OSE, and observed sweat loss data) against the output from piecewise equation show high r values (0.96, 0.88, and 0.78, respectively).

However, these r-values cannot quantitatively verify the individual segmentation in response.

Figure 3. Output from OSE, exponential correction to OSE and observed sweating rate plotted against piecewise regression output. Negative exponential smoothing is denoted by solid lines in the data.

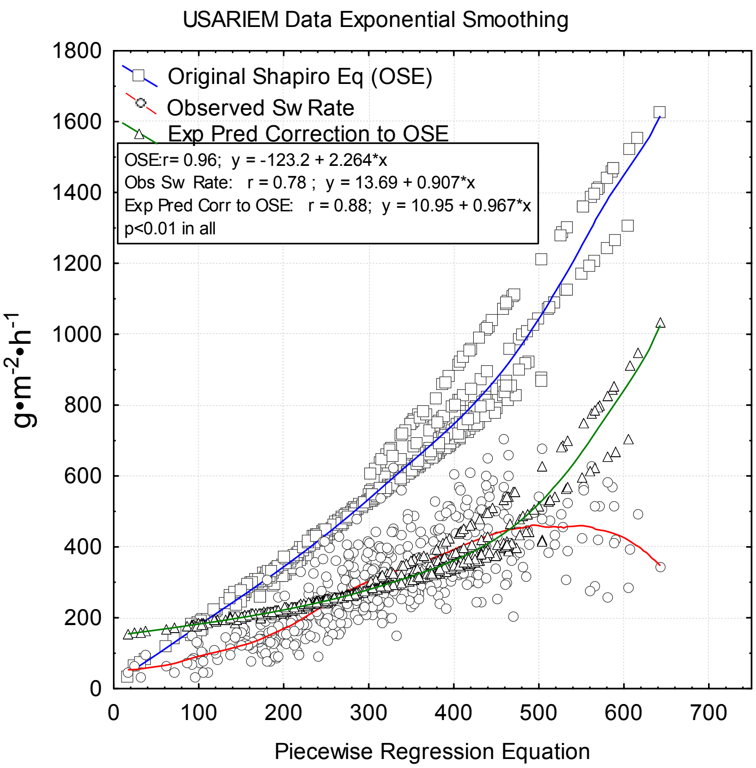


Figure 4. Sweat loss ($g{\bullet}m^{-2}{\bullet}h^{-1}$) output (means ±95% confidence intervals) from the various equations and observed data plotted vs. the given trials. Values are staggered for clarity. Double asterisk (**) for the OSE prediction shows significant differences between trials and right bracket (]) between other curves at p<0.003 (Bonferroni). There is a non-significant difference between the other prediction equations and observed sweat loss for each trial.

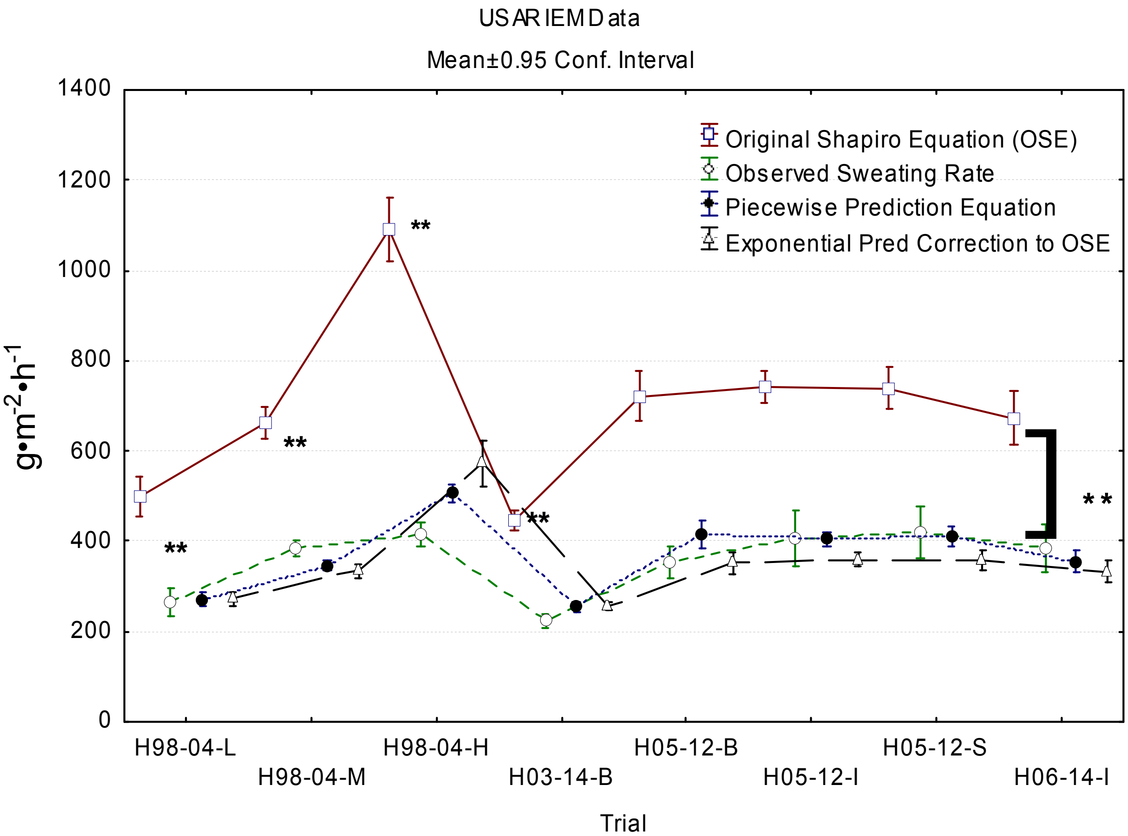


Figure 4 above shows a comparison of the output from the various prediction equations along with the observed sweat rates lumped for each trial run. The OSE showed the widest variability compared to the observed data and was markedly elevated for the moderate and heavy work intensity experiments. However, the corrected prediction equation tracked output response remarkably well in comparison to the observed data and piecewise prediction equation.

Figure 5. Predicted sweat rate responses plotted vs. observed sweat rate for all trial data.

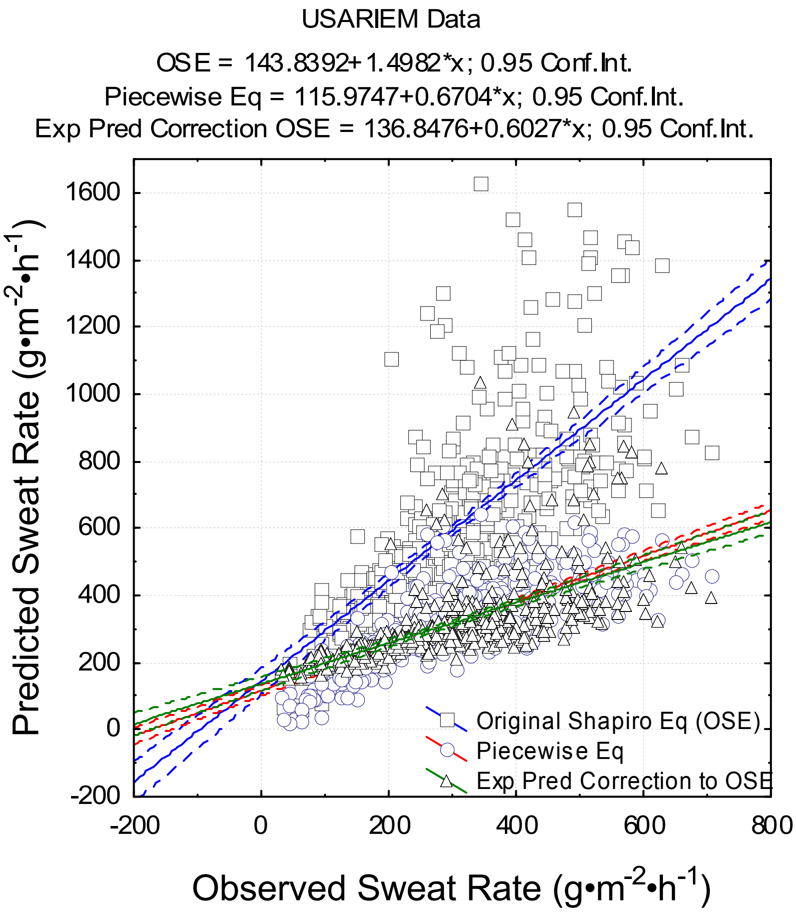
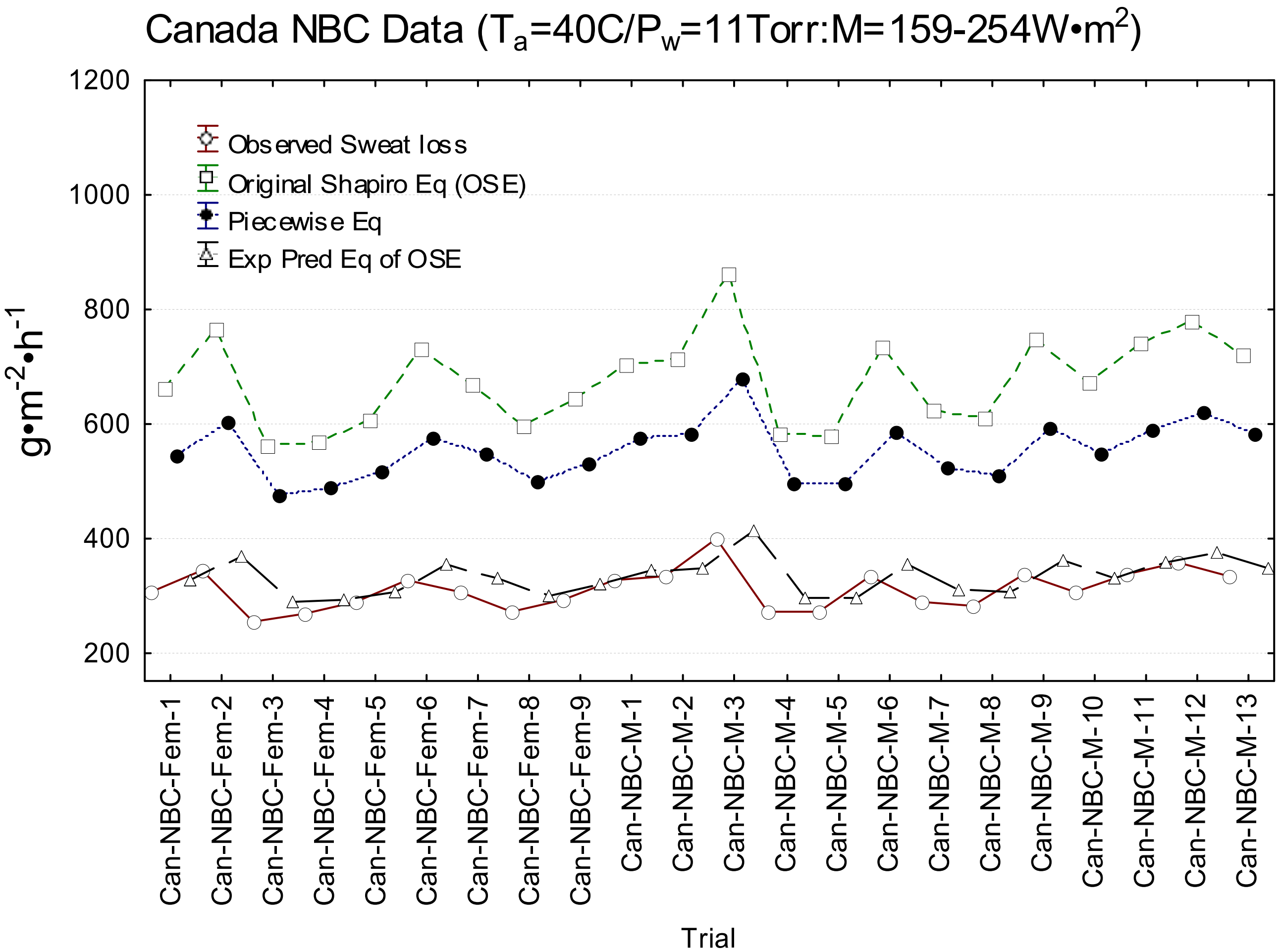


Figure 5 shows the output from the various prediction equations plotted against observed data. Noticeable is the fact that the output from the original Shapiro equation overpredicts by almost 66% above 500 $g{\bullet}m^{-2}{\bullet}h^{-1}$, and below that range the scatter is widespread. Using the corrected equation compares well with the piecewise regression equation, but the scatter is still prevalent.

Cross Validation Analysis from Two Separate Studies

Figure 6A. Output from the various prediction equations and observed sweat rate plotted for each subject in a Canada NBC study.



To see how well the various prediction equations track individual response data, a comparison test was done using separate study results: one using field data and the other using a laboratory study conducted outside USARIEM. The outputs from the various prediction equations, as well as the observed sweat loss, are shown in Figure 6A.

The OSE predicted sweat loss response higher than observed data consistently across subjects ($p<0.003$), but so did output generated from the piecewise regression equation (by about 50% less). It is not clear, at this time, why this occurred. One reason may be that the experimental runs during this trial were conducted at chamber wind speed of 0.4 m/s, while the dynamic im/clo evaluated for the clothing system had been at 1 m/s. The evaporative heat transfer coefficient strongly coupled with skin wettedness (8) (ωh_e, $W \cdot m^{-2} \cdot Torr^{-1}$) and other heat balance parameters in the original piecewise regression coefficients that are used to calculate E_{req} and E_{max} are co-mingled with free and forced convection and possibly not sensitive to low wind speed. Therefore, latent heat transfer within layers of chemical protective clothing is calculated at a higher value. Interestingly, the corrected equation to the OSE matched the observed sweating rate responses between subjects.

Figure 6B. Output from each prediction equation plotted vs. observed sweating rate.

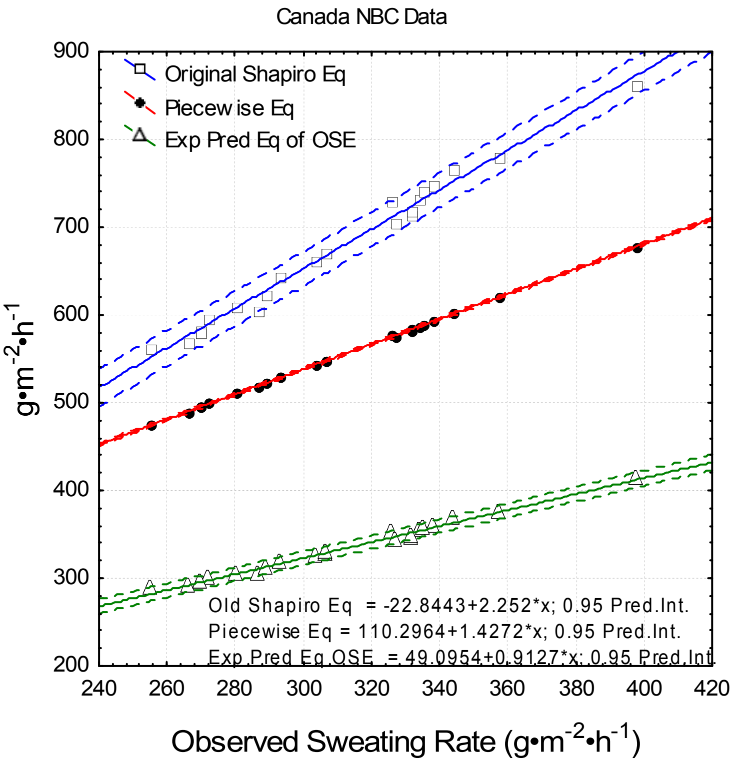
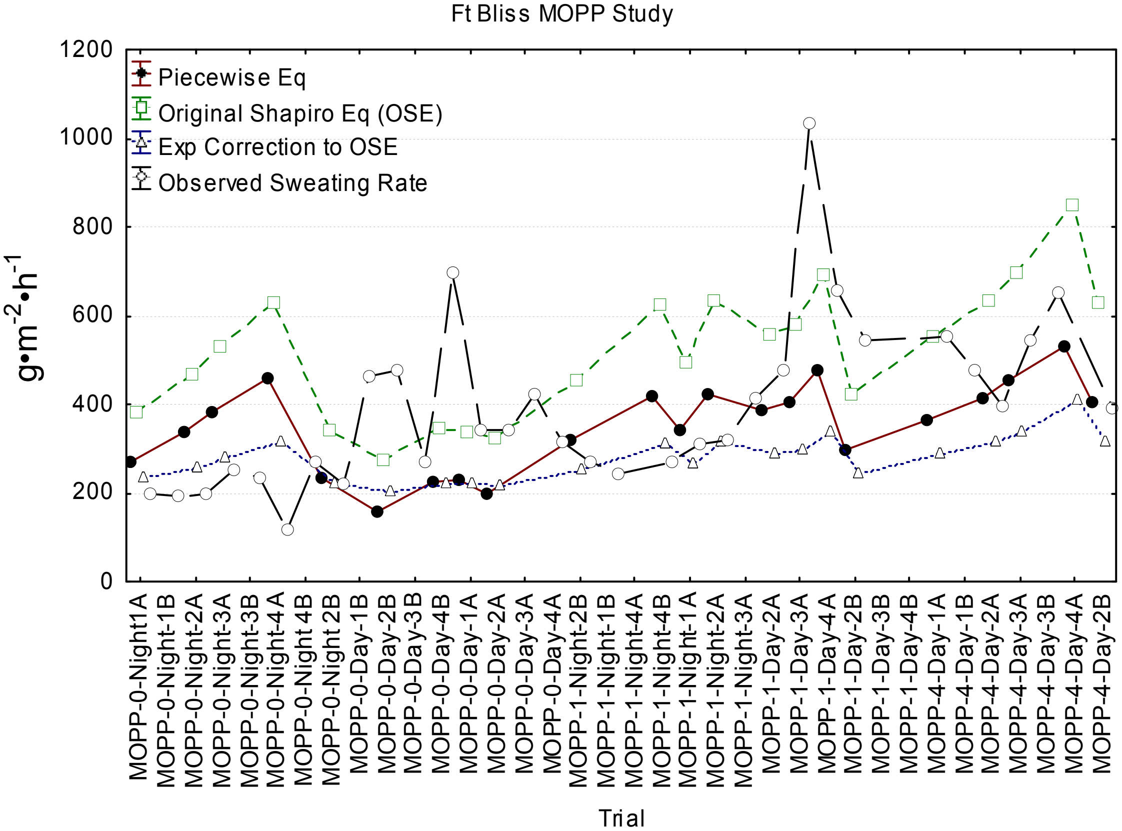


Figure 6B shows this fact more clearly when the output from each of the 3 prediction equations is regressed against the observed sweating rates. The corrected equation matches the observed data. However, in the linear plot analysis, the regression coefficient (1.427) of the piecewise regression equation is significantly higher ($p<0.003$) than the one evident from the corrected OSE (0.912). This indicates that the latent heat loss may be elevated falsely particularly between the interstices of military chemical protective clothing layers. Additional research is required to investigate this property.

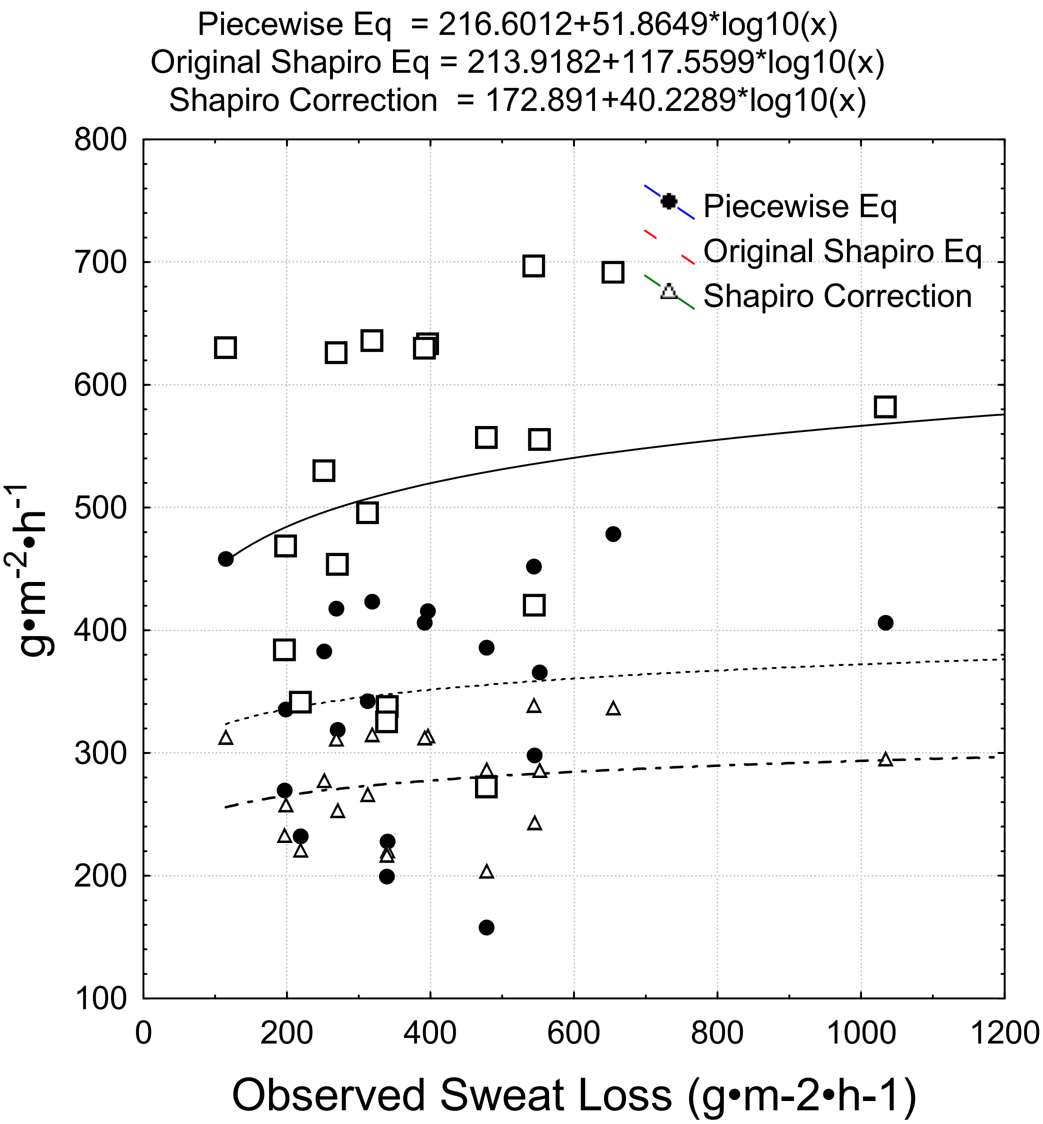
Figure 7A. Output from each of the prediction equations and observed sweat loss plotted for each individual walking in MOPP clothing.



The outputs from the various prediction equations and observed sweat loss during a field study test (29) are shown in Figure 7A. In general, the piecewise regression and corrected OSE equations predicted individual sweating rates adequately (within the ±150 $g \cdot m^{-2} \cdot h^{-1}$ criterion deviation) except for a few individuals. The OSE, however, consistently predicted too-high values.

This response is more clearly evident in Figure 7B in which the above data are transformed into logarithmic form and plotted in linear coordinates. The OSE regression coefficient (117.6) is significantly higher than the other two reqression coefficients (p<0.001). The regression coefficients from the outputs using the piecewise regression equation and the corrected OSE are not significantly different and each follows the observed data more closely than the OSE.

Figure 7B. Log plot of the outputs from the prediction equations vs. observed sweat loss.



DISCUSSION

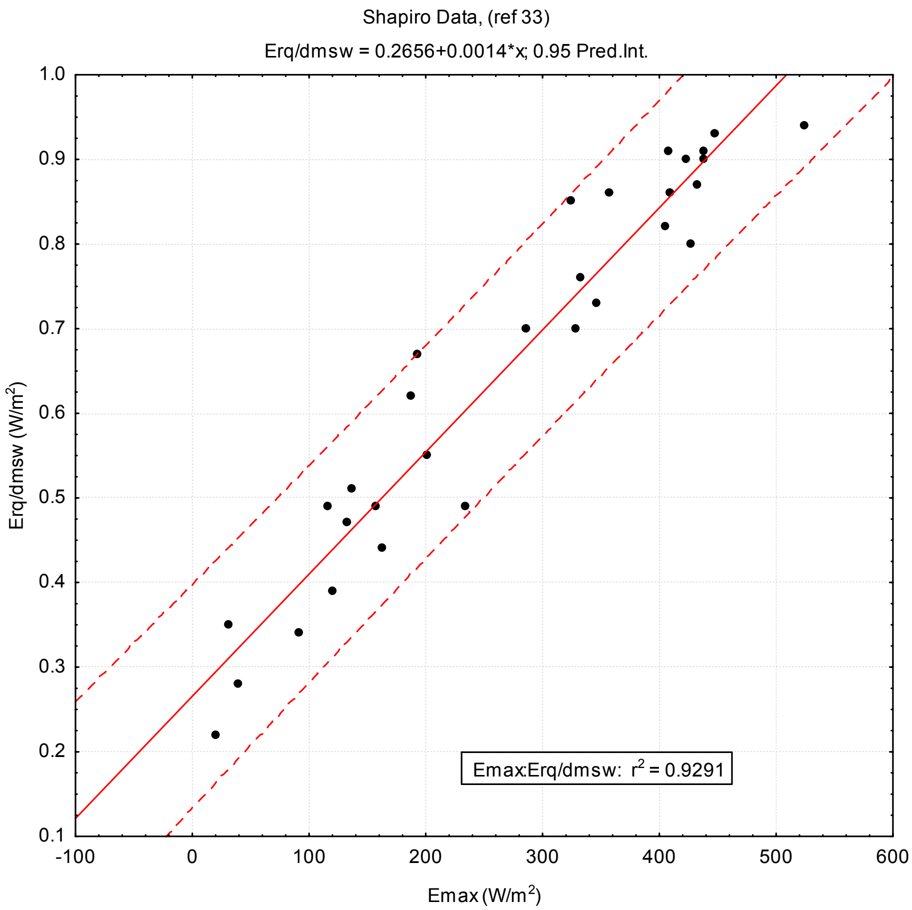
The objective of this project was to cross validate (using new data) the original equation that was developed by Shapiro et al. (33) to predict rate of sweat loss over wide environmental conditions, clothing systems, and metabolic activities, which did not include women responses in its formulation. The rationale to develop a predictive equation to gauge sweat loss (and, thereby, water requirements) was a unique concept at the time. This equation has been used to predict water requirements over wide thermal environments by knowledge of only two key variables, E_{req} and E_{max}, which directly or indirectly integrate the effects of the internal factors (M, skin and core temperature) and external factors (clothing, operative temperature, wind, and humidity). Within the limits of the data, the equation has been shown to be a valid estimator of sweating rate for a variety of heat stress exposures of up to 2 h and work rates limited to less than 450 W.

The next objective was to develop a new prediction algorithm, or correct the previous one so that reliable fluid replacement guidelines using such equations can be constructed in the future for more extended work times greater than just 2 h, the exposure time present in the original study database. The need to develop a new prediction equation stems from results of recent studies (4,5,22; Xu, personal communication, 2007) that revealed that the original Shapiro equation embedded in a Heat Strain Decision Aide (HSDA) computer model tended to overpredict actual sweating responses over wide environmental extremes, work rates, and work periods. The consequences are that overpredictions of sweating rate (and the required predicted fluid intake to fully replace the expected sweat loss especially during extremes of heat loss) can lead to over-hydration problems (10,23,26).

To accomplish these objectives, a wider database was necessary that includes heavy exercise, modern clothing systems including body armor, and incorporated sweating responses from both men and women. The present study includes such data (over 100 subjects).

A critical shortcoming was found in the data that produced the sweat loss prediction equation (Eq. 1) selected from the original reference data (33). This scrutiny revealed that the equation was developed by a relationship of $E_{req}/\Delta m_{sw}$ plotted against E_{max} using averaged data from three series of experiments in which Δmsw is sweat loss ($g \bullet m^{-2} \bullet h^{-1}$). This regression equation ($Y=0.0537(E_{max})^{0.455}$) was then solved as $\Delta m_{sw} = E_{req}/ 0.0537(E_{max})^{0.455}$ to obtain 18.6 (the reciprocal of 0.0537) x $E_{req}/ (E_{max})^{0.455}$ and converted by division of the latent heat of vaporization of sweat (λ, J/g) to obtain the final equation present in HSDA model. A linear approximation would have satisfied the averaged data, and it is not certain why this was not pursued in the data set, as evident in Figure 8.

Figure 8. Original data from Shapiro estimated by a linear reqression of E_{req} /dm_{sw} vs. E_{max} (r^2=0.929). In addition, the solution of the above equation for dmsw is 714E_{req}/(E_{max} +190), W/m^2, or 1050E_{req}/(E_{max} +279) g•m^{-2}•h^{-1}.



Another key shortcoming of such analysis evident from the original report (see Figure 4, Shapiro et al., (33)) is the use of average data solely to obtain a final equation, which inherently biases the residual sum of squares (lessens its variance) in a regression analysis shown in Figure 8. Also, the λ unit used was incorrect, which Wenger (37) showed is 2,426 J/g (0.68 W•h/g), thereby resulting in the sweat loss prediction equation being:

$$\text{Sweating rate } (g \cdot m^{-2} \cdot h^{-1}),\ \Delta m_{sw} = 27.4 \cdot E_{req} \cdot (E_{max})^{-0.455} \qquad \text{(Eq. 4)}$$

Additionally, the assumption is incorrect that E_{req}/ Δm_{sw} is not a correlate of M (metabolic heat production), when in fact E_{req} is based on the solution of the comprehensive heat balance equation comprising M-W-(R+C)- S. Another limitation in the original sweat loss equation, that is now embedded in the HSDA, is the capitation of mean skin temperature to a value of 36.5°C, rather than allowing skin temperature to "float" at the specific level for a given work intensity and environmental challenge where steady-state heat balance can be obtained. This skin temperature (and skin saturation vapor pressure, $P_{s,sk}$) increases dry heat (R+C) and latent heat losses (elevating the $P_{s,sk}$ to ambient vapor pressure gradient through contiguous clothing layers) and artificially raises the predicted sweating rates at a given time point, possibly initiating an overprediction in total sweat loss.

In the present study, output from the original Shapiro prediction equation consistently overestimated measured rate of sweat loss during high intensity exercise up to a maximum in every trial from both the present database and the archival data. Maximal sweating rate is generally limited to about 667 $g{\bullet}m^{-2}{\bullet}h^{-1}$, a value close to 1.27 L/h for a person with a BSA of 1.9 m^2 (38,39). Above that value, a person generally cannot reach values necessary to achieve steady-state heat balance.

A reevaluation of the original Shapiro algorithm using the present extensive database (101 subjects, longer work durations from 4-8 h, and a variety of clothing systems) established that the original equation for Δm_{sw} does indeed statistically predict markedly high values in sweating rates**.** Therefore, water requirements using the equation would also predict too-high fluid requirements and concur with recent studies (4,22) showing similar over-estimations using that equation.

The most important accomplishment of the current analyses was the development of an improved equation:

$$m_{sw}\ (g{\bullet}m^{-2}{\bullet}h^{-1}) = 147 + 1.527{\bullet}(E_{req}) - 0.87{\bullet}(E_{max}) \qquad \text{(Eq. 2)}$$

based on fuzzy piecewise regression analysis that incorporates the combined effects of wider metabolic intensities, body armor and clothing systems, and is essentially applicable for both men and women working for longer time periods than 2 h if proper work:rest cycles are interposed. The equation still incorporates attributes of the original Shapiro equation: one related to solution of the heat balance equation (E_{req}) and the other associated with clothing worn and environmental impact (E_{max}).

Additionally, a correction to the original equation modeled from similar concepts was constructed in which:

$$m_{sw}\ (g{\bullet}m^{-2}{\bullet}h^{-1}) = 147{\bullet}\exp(0.0012{\bullet}OSE) \qquad \text{(Eq. 5)}$$

where OSE is output from the original equation that may be employed to predict water requirements to replace fluid lost from sweating within ±0.125 mL/h. The limits of the above predictive equations comprise the original E_{req} and E_{max} limits ($50<E_{req}<360$ W•m^{-2} and $20<E_{max}<525$ W•m^{-2}, respectively), but extends these limits so the algorithm is applicable for higher work intensities (M=400 W•m^{-2}, ~700-800W) and lower ambient conditions (T_a=15°C).

One factor that was not addressed in this study and awaits further study is the importance of the relationship of sweating rate and VO_2 max. Greenleaf et al. (17) found a linear relationship between these factors during 2-h exercise bouts in the heat. Also, compared to unconditioned subjects, physically fit subjects (VO_2 max ≥ 65 ml•kg^{-1}•min^{-1}) showed some 230% greater sweating rates than the unconditioned subjects. Applying these results to the present study suggests that highly fit subjects would saturate the thermoregulatory sweating response system faster and E_{req} to achieve heat balance would occur earlier. However, during uncompensable heat stress conditions, excessive sweating with little evaporation would lead to early water saturation of a given clothing system, possibly changing the latent heat loss dynamics through the system. It is uncertain whether the above prediction equations would be supported.

Another factor not addressed by this study was the sweat prediction analysis using another model's output, briefly explained in the Introduction. The SCENARIO model uses the thermoregulatory control sweating equation put forth by the work of Nadel and co-workers (24). The equation is embedded in the model's code, and sweating rates are solved based on changes in core temperature and skin temperature output using the following format, where the prediction of sweating rate (g•min^{-1}) is:

$$m_{sw} = A_D \bullet \phi_{sw} \bullet \left[\alpha(T_{bl} - T_{bl,o}) + \beta(T_{sk} - T_{sk,o})\right] \exp \left(T_{sk} - T_{sk,o}\right)/10 \qquad \text{(Eq. 6)}$$

In the equation above, A_D is BSA area (m^2), α is the control coefficient (4.83 g•min^{-1}•°C^{-1}) modifying the change in blood temperature (i.e., bathing the hypothalamic thermoregulatory center, Tbl,x, °C) at a given time based on exercise or other factors from an arbitrary hypothalamic set point (Tbl,o = 36.96°C), and β is the control coefficient (0.56 g•min^{-1}•°C^{-1}) driving the change in average skin temperature (Tsk,x, °C) from a thermoneutral set point (Tsk= 33.0°C).

The parameter ϕ_{sw} (units of g•m^{-2}•min^{-1}) in the SCENARIO model is a new critical factor driving all variables. This factor was originally based on the linear relationship between sweating rate output (g•m^{-2}•min^{-1}) induced by pilocarpine iontophoresis and VO_2max (2). The relationship was evaluated for both men and women with maximal aerobic capacities ranging from 33 to 78 ml•kg^{-1}•min^{-1}. In this format, we see that ϕ_{sw} = 0.16•VO_2max -3.16 (and the maximum aerobic power of an individual) modifies explicitly the overall sweating output determined by the changes in internal body and skin temperatures. The above equation has only been validated for minimally dressed individuals and may not hold for wider environmental challenges. More studies are called for investigating this crucial property on the control of thermoregulatory sweating.

Indeed, by using the wealth of data on 2-mile run times (generally used in U.S. Army physical fitness testing) garnered by the U.S. Army (19), it would be a straightforward undertaking to predict VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$) using the following:

for women: $VO_2max = 72.9 - 1.77x$ (r= - 0.892) (Eq. 7)

and for men: $VO_2max = 99.7 - 3.35x$ (r=-0.906) (Eq. 8)

where x is the given 2-mile run time completion (min).

The parameter ϕ_{sw} could then be determined from these data and used as input in the above algorithm to derive sweating rate and, therefore, the required fluid intake at VO2max, or a percentage of the aerobic capacity to accomplish a given military task.

Montain (22) found that the sweating output using the SCENARIO model also overpredicted responses compared to measured sweating rates, averaging some 0.27, 0.58, and 0.57 L/h less than predicted for WBGT environments of 25.6°, 29.5°, and 33.3°C, designated as heat category I, III, and V conditions, respectively. Additionally, in comparing the HSDA and SCENARIO models, Xu (unpublished report, 2007) found model prediction levels were some 20% higher than observed values using averaged data from Cheuvront's study (4).

All the above results would suggest that output from prediction models should be employed with caution and not hastily used outside the limited range of climatic conditions, clothing variables, and physiologic and heat exchange variables that were not originally specified when formulating a mathematical model.

CONCLUSIONS

- In conclusion, the results from the current project verify that the original equation used to forecast sweat loss over wide heat stress conditions predicts too-high values for the data set evaluated, as shown in Figures 5-6.
- The original sweat loss equation (OSE) = $27.9 \bullet E_{req} \bullet (E_{max}^{-.455})$ is based on a limited data set, old static manikin analyses, restricted to male responses, and short exposure times (≤ 120 min).
- Caution should be taken when using any prediction models to develop guidelines for fluid replacement based on sweat loss prediction.
- The tactic used in a fluid replacement recommendations report by Montain et al. (22) is a good rational approach, whereby a conservative assessment is taken to prevent over-hydration by not drinking more than 12 $L \bullet day^{-1}$ coupled to a given heat stress condition and work intensity of the individual.

RECOMMENDATIONS

It is recommended that the findings within this report be used to substitute or modify the current HSDA program with corrected algorithm s below:

$$\text{Sweat loss } (g \bullet m^{-2} \bullet h^{-1}) = 147 + 1.527 \bullet (E_{req}) - 0.87 \bullet (E_{max}) \qquad \text{(Eq. 2)}$$

This equation was found to take into account effects of heavy work and clothing factors, body armor effects, longer exposure times (2-8 h), residual errors inherent in the original equation to predict sweat loss, and is not gender specific.

Alternatively, a correction to the original equation can be used as a simple replacement, determined as:

$$\text{Sweat loss} = 147 \bullet \exp(0.0012 \bullet OSE) \qquad \text{(Eq. 5)}$$

These equations require testing over wider effective radiant loads in the field (effect of Solar Load, Shapiro et al., (32)) using a larger database. The findings within this report serve as a first order approach that may allow better prediction of individual water requirements and/or sweat loss response useful in field trials.

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APPENDIX A

The heat balance in W•m^{-2} of BSA (A_D, m^2) is expressed by (9):

$S = M - Wk - E - (R + C)$ (Eq. A-1)

where,

[1]*S* = the time rate of change of body heat (gain or loss);

M = the rate of metabolic heat production;

*W*k = the rate of accomplished mechanical work;

E = the rate of evaporative heat loss via regulatory sweating from eccrine sweat glands, diffusion (Edif), respiration (Eres), and metabolic heat loss $m_{r;}$

C = the rate of convective heat loss from the total body surface and respiration;

R = the rate of radiant heat loss (or gain from) the surrounding surfaces.

RADIATION EXCHANGE

In any thermal environment, a linear radiation transfer coefficient may be derived (9,25) by:

$h_r = 4 \cdot \alpha \cdot \sigma \cdot (A_r/A_D) \cdot f_{cl} \cdot (5.67 \times 10^{-8}) [(T_o + Tsurf) / 2 + 273.15]^3$, $W \cdot m^{-2} \cdot °C^{-1}$ (Eq. A-2)

where,

α is the skin or clothing absorptance for the radiation exchange to the ambient;

σ is the Stefan-Boltzmann constant (5.67×10^{-8}, $W \cdot m^{-2} \cdot K^{-4}$);

the factor A_r/A_D represents the ratio of the effective radiating area of the human body to the total BSA, as measured by the Dubois surface area formula (=0.72 for standing individuals). The interior environmental temperature is composed of an average of the operative temperature + all the surface temperatures (T_{surf}) including any clothing surface temperature (T_{cl}); f_{cl} represents a factor which increases the effective A_r of the body surface by some 15% per clo (9,18). Mean

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[1]The heat balance equation is, by definition, expressed as rate of exchange over time, so the italics replace use of an overdot in this report.

clothing surface is derived by $\bar{T}_{sk}$ in the relationship $[T_o + F_{cl} \cdot (\bar{T}_{sk} - T_o)]$. For shorts+T-shirt $F_{cl}=1$, and $T_{cl} = \bar{T}_{sk}$.

CONVECTIVE EXCHANGE

This is represented by free convection and forced convection via increased metabolic activity, or increased room air movement artificially. Two equations for estimating the convective heat transfer coefficient have been formulated based on a composite of free and forced convection (25):

$$h_c = 1.2 \left[(M - 50) \left(P_B/760 \right) \right]^{0.39}, \ \mathrm{W \cdot m^{-2} \cdot {}^\circ C^{-1}} \qquad \text{(Eq. A-3)}$$

where, M is the metabolic activity in $\mathrm{W \cdot m^{-2}}$ and P_B is the barometric pressure in Torr (1kPa/7.5Torr). Alternatively, h_c for fan generated forced convection, in which ambient air movement (V, $\mathrm{m \cdot s^{-1}}$) is the main factor affecting convective heat exchange, can be expressed by either (h_c in $\mathrm{W \cdot m^{-2} \cdot {}^\circ C^{-1}}$):

$$h_c = 8.6 \left[V \cdot P_B/760 \right]^{0.53} \qquad \text{(Eq. A-4)}$$

when persons are dressed in shorts and T-shirts or by:

$$h_c = 12.7 \left[V \cdot P_B/760 \right]^{0.50} \qquad \text{(Eq. A-4')}$$

when persons are clothed (9,18,25).

APPENDIX B

Woodcock and Breckenridge's (1) procedures applicable to clothing heat transfer were used to calculate environmental heat exchange. These methods consider the skin, clothing, and environment as a total system and the constants defining insulation and water vapor transfer as functions of effective air movement (v_{eff}). v_{eff} is the sum of air motion around a stationary object plus the speed at which the object is moving. I_T (v_{eff}) is the total resistance to heat flow by radiation and convection (in clo units, 1 clo is equivalent to 0.155 $m^2K•W^{-1}$or thermal conductance of 6.45 W $m^{-2}K^{-1}$), and i_m (v_{eff}) is the relative total resistance to evaporative heat transfer (zero to one, dimensionless). In heat balance calculations, I_m is not used alone but as a latent heat transfer coefficient (i_m / I_T), evaluated in an articulated, moving, sweating manikin; this latter quantity is considered as a key dynamic constant incorporating both heat and mass transfer via "pumping" through cuffs, vents, and walking, as well as relative permeation from skin to ambient, important in total latent heat transfer efficiency of military clothing.

Values for I_T and (i_m /I_T) as a function of v_{eff} should always be taken into account in calculation of E_{req} in the summed heat balance whenever there is a change in the clothing system via exercise or use of body armor (dynamic effects). These clothing parameters can be calculated from the following power curves automatically estimated on the sweating, articulated manikin used to evaluate clothing ensembles (12):

$$I_T = A•v_{eff}^{\,B} \quad \text{and} \quad (i_m / I_T) = C•v_{eff}^{\,D}, \qquad \text{(Eqs. B-1, B-2)}$$

where the coefficients A and C are the values for I_T and (i_m / I_T) when v_{eff} = 1.0 $m•s^{-1}$ and the coefficients B and D are slopes of plots of ln (I_T) and ln (i_m / I_T) vs. ln (v).

The intrinsic thermal insulation value, I_{int} (v), is obtained by subtracting the value of the insulation of the air boundary layer, I_{acl}, from I_T:

$$I_{int} = I_T - \frac{1}{(f_{acl}) \bullet (0.61 + 1.87\sqrt{v_{eff}})} \qquad \text{(Eq. B-3)}$$

where $\tilde{f}_{acl}$ in Eq. B-3 is the increase in surface area due to clothing that is estimated (1) using:

$$\tilde{f}_{acl} = 1 + (0.2 • A_D). \qquad \text{(Eq. B-4)}$$

Breckenridge (1) defined the algebraic sum of the total (DRY) heat loss by radiant and convective heat exchange (R+C), watts as:

$$Dry = (R + C) = \frac{6.45 \bullet A_D f_{acl}}{I_{int}} \left[\frac{0.61(\bar{T}_{sk} - \bar{T}_{mr}) + \sqrt{v} \bullet (Tsk - Ta)}{\frac{1}{I_{int}} + f_{acl}(0.61 + 1.87\sqrt{v})} \right] \quad \text{(Eq. B-5)}$$

INSENSIBLE HEAT LOSS

E is determined by the rate of sweat secretion ($\underline{m}_{sw}$) and the maximal rate of evaporative heat loss from a fully wetted skin surface (E_{max}). E_{max} is a function of the vapor pressure gradient between the fully wetted skin surface and the air ($P_{s,sk}$ - P_w), the evaporative heat transfer coefficient (h_e) and i_m, Woodcock's dimensionless factor for permeability of water vapor through clothing. The evaporative heat transfer coefficient, h_e, is directly related to the convective heat transfer coefficient, h_c, by the Lewis Relationship (LR, 2.2°C/Torr or 16.5 K/Kpa) (9).

When evaporation is not restricted by clothing or the environment, then:

$$E_{sk} = \dot{m}_{sw} \bullet \lambda \quad \text{(Eq. B-6)}$$

where $\dot{m}_{sw}$ is in $g \bullet h^{-1}$ and λ is the heat of vaporization for sweat at 35°C (0.68 $W \bullet h \bullet g^{-1}$), Wenger (37). The expression for E_{sk} under conditions where evaporation of sweat is restricted and there is frank dripping (Edrip) or wasted sweat due to skin wettedness (ω) > 1.0 is (8):

$$E_{sk} = (0.06+0.94 \bullet \omega) \bullet A_D\ E_{max} = (LR \bullet 6.45)\ A_D \bullet (i_m/I_T) \bullet (P_{s,sk} - P_w), \quad \text{(Eq. B-7)}$$

when $E_{max} \leq \underline{m}_{sw} \bullet \lambda$

where A_D is the DuBois surface area (m^2) (1,9): $P_{s,sk}$ (in Torr) is the vapor pressure of saturated air at skin temperature. $P_{s,sk}$ is related to $\underline{T}_{sk}$ by the Antoine Equation (9):

$$P_{s,sk} = \exp\left((18.6686 - \frac{4030.183}{T_{sk} + 235} \right) \quad \text{(Eq. B-8)}$$

RESPIRATORY HEAT LOSS

(C_{res}+E_{res}) is directly related to ventilation rate which, in turn, is directly related to aerobic exercise intensity (M_{tot}) up to maximal levels. The combined equation for estimating respiratory loss by convection and evaporation is taken from (21) for high levels of exercise as 0.019•$\dot{V}_{O_2}$(44-Pw) in g/min):

$$(C_{res} + E_{res}) = A_D \bullet M_{tot}\,[0.0014 \bullet (34 - T_a) + 0.0023\,(44 - P_a)] \quad \text{(Eq. B-9)}$$

E_{res} is also modified by a constant (F) for high levels of exercise (28), so that if $\dot{V}_{O_2}$ < 2.6 L/min, F =1 and if > 2.6, F = 1 +0.106($\dot{V}_{O_2}$-2.6)^2. (Eq. B-10)

EVAPORATIVE HEAT LOSS CORRECTION FOR METABOLIC HEAT LOSSES BY CO2 AND O2 ($\dot{m}_{res}$)

If the Respiratory exchange ratio (R) is = 1, $\dot{m}_{res} = \dot{V}_{O_2}(R \bullet \rho CO_2 - \rho O_2)$, g/min, (Eq. B-11)

where ρCO_2 = density of CO_2= 1.96 g/L STPD,
and ρO_2 = density of O_2= 1.43 g/L STPD and $\dot{m}_{res}$=0.53•$\dot{V}_{O_2}$; if R > 1,

$$\dot{m}_{res} = VO_2\,(R \bullet 0.53) \quad \text{(Eq. B-12)}$$